

Simplesat-1 Experiment Final Report



David R. Skillman, P.I. Laser Remote Sensing Branch

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Simplesat-1 Experiment Final Report

Goals of this Internal Review

- Technical evaluation the Simplesat concept
- List technical strengths/weaknesses
- Define additional steps, within the original cost boundaries, that would increase the likelihood of success
- Provide to management advice as to whether a Simplesat-2 should be attempted

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Requirements and Goals for the SimpleSAT DDF

- Engineering experiment requirements:
 - Design/construct/orbit/operate a 3-axis inertially stabilized spacecraft
 - Demonstrate one degree coarse attitude accuracy (GPS)
 - Design for minimal infrastructure support requirements
 - Maximize usage of commercial components
 - Minimize costs (\$200k for parts, 5 man-years of labor)
 - Target HH ejection capability (150 lb, 19” dia, 26” length)
- Engineering experiment goals:
 - One month nominal lifetime
 - Autonomous operation to minimize ground station requirements
 - Thermal performance characterization
 - Demonstrate one arcsec fine attitude accuracy and stability via CCD camera
 - Demonstrate pattern recognition to find target
- “Science” goals:
 - Low-speed photometry of variable stars

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Spacecraft Characteristics

- **Mass: 52 kg**
- **Size: 66 cm tall, 50 cm diameter (26" x 19" dia)**
- **Telescope: 30 cm diameter optics, commercial CCD camera detector**
- **Power: 15 watts orbit-average from solar cells mounted on body
14 amp-hr NiCd battery**
- **Attitude: Three-axis stabilized, inertial pointing**
- **Attitude sensor: Four channel GPS receiver**
- **Pointing Control via three reaction wheels
1 degree (GPS)
1 arcsec (star images from camera)**
- **Momentum control: Torque coils**
- **Computer: commercial single board computers**
- **Communications: 4800 baud to GSFC via ham radio equipment**

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Equipment not needed

- Voltage regulators (all equipment ran on unregulated power)
- Torquer bars
- Gyroscopes
- Earth sensors
- Sun sensors
- Star trackers
- Magnetometers
- Nutation dampers
- High RPM reaction wheels
- Thermistors
 - (Simplesat had 131 temperature sensors served by two wires)

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Project Summary

- Funded by Director's Discretionary Fund
- SimpleSAT-1 spacecraft designed to use industrial components
- Innovative system design eliminated complex components
- Tried to find out "where the money goes" at all stages
- Spacecraft/instrument/ground station constructed for less than \$200k+5 MY
- Met all STS safety tests/inspections/analyses
- Placed in orbit using HH ejection system by STS-105 in August 2001
- B33 ground station was unable to contact the spacecraft in orbit
- Re-entry in late January 2002
- Problem analysis conducted
- Possible failure mode identified (transmitter arcing)

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Concept

- Not intended to be a “new way of business” for GSFC projects
- Aimed at institutions with little space program infrastructure (i.e. universities)
- Design a small limited-lifetime satellite to utilize the existing HitchHiker ejection capability (150 lbs, 0.5m dia) to place a small object into orbit
- Take advantage of the ISS-intensive STS schedule to gain access to orbits that pass over most of the continental U.S. (52 deg inclination). These orbits permit ground stations at any university
- Accept risk (Class D or lower)
- To control costs:
 - Use recent GPS developments to achieve inertial attitude sensing
 - Use ham-radio equipment and techniques for communication
 - Use industrial components instead of space-qualified components
 - Put complexity into software rather than hardware
 - Limit amount of testing
 - Limit expectations by “experiment” vs. “mission”
 - No clean room requirements or specialized facilities
 - Inserted into orbit with batteries discharged to avoid safety issues

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Potential Future Simplesat-like Demonstrations/Missions

- Cataclysmic Variable Observer Mission (astronomy)(Simplesat-1)
- GAMES (Gravity and Magnetism Earth Survey) demonstration
- Selected Area Laser Altimeter Missions (mini-GLAS)
- Radiation Environment Heritage Generator Mission (JPL)
- SOLAR J2 sensor/propulsion demonstrator (Code 920)
- Spectrographic Monitor Mission (astronomy - Columbia University)
- RTOP generic mini-mission (aircraft replacement)

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Approach

- Use PI or student labor wherever possible
- Build breadboard for testing and debugging pre/post launch
- Minimize the use of NASA infrastructure
 - try to construct and test using typical University resources
- Use NASA for guidance and to supply specialty items, not as a resource for labor and materials.
- GSFC support:
 - first-order mechanical design to assure safety
 - use NASA-procured fasteners
 - provide materials guidelines and advice (e.g. HitchHiker/Code 300)
 - convert commercial GPS equipment for space operation
 - attitude control law development
 - special materials procurement (i.e. hysteresis rods, KOH absorbers)

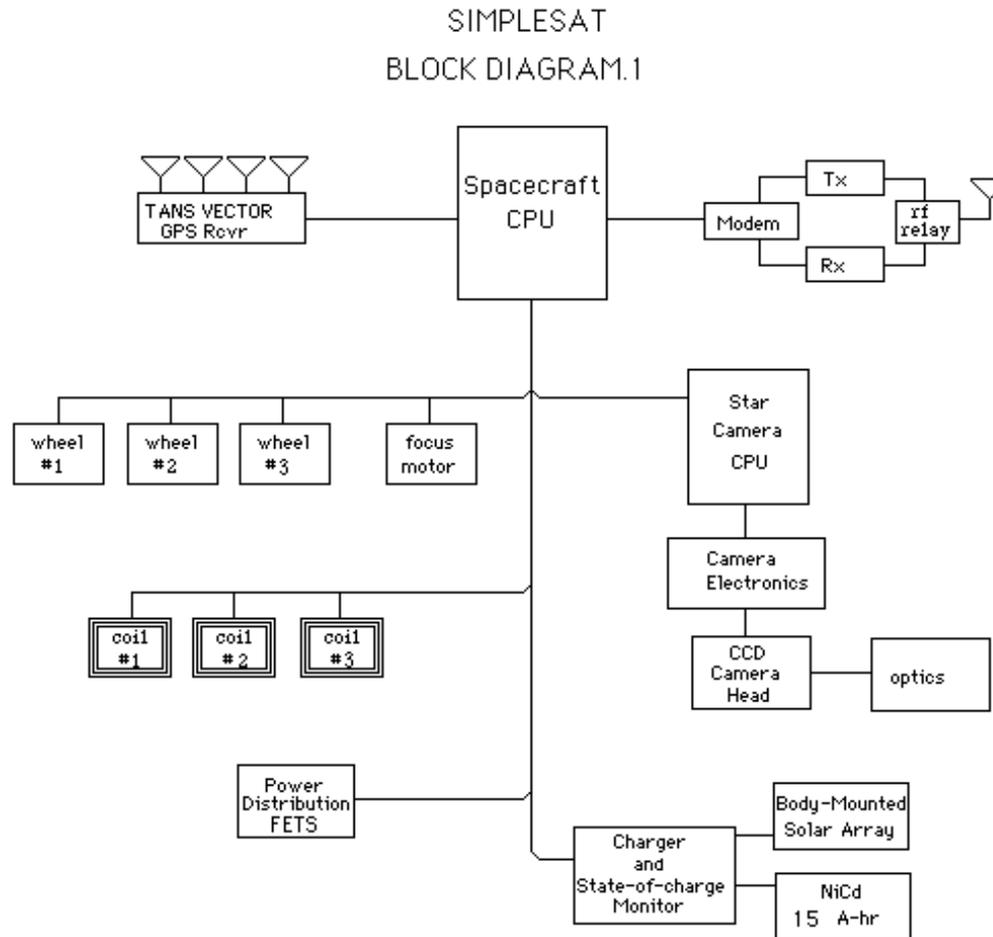
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Design Elements

- Minimize external attitude disturbances
 - reduces size/cost of attitude control actuators
- Use stepper motors for reaction wheel drive
 - cheap, simple to control open-loop
 - safe, phase controllable
- Detumble body with magnetic hysteresis rods
 - cheap, passive, dependable, good for safemode
- Selected stellar-observing instrument as baseline science
 - provided design requirements
 - could supply fine guidance sensing

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Design: Electronics Block Diagram



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Design: Cost control

- Adapt optics from commercial telescope
 - 12” Meade catadioptric system
 - entrance window provides contamination protection and thermal isolation
 - focussing was a problem
- Use midrange silicon solar cells (14% efficient)
 - cheap, workable, local knowledge from university solar race cars
 - body-mounted cells limit power (35w max, 15w orb-avg)
- Adapt aircraft GPS unit (Trimble TANS Vector) as attitude sensor
- Hand-wound body coils to act as magnetic torque actuators
- All aluminum structure
- Commercial parts wherever possible
- Wire-wrapped circuit boards
- PI and volunteer software

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Design: Flight software

- Calculate positions of Sun, targets, and the Earth in ECI coords
- Use mathematical models for orbit propagation
 - downlink times calculated by spacecraft
 - local magnetic field strength
 - orbit event scheduling of subsystems (science instrument, GPS,...)
- Use attitude/mag-field information to minimize reaction wheel momentum
- Monitor temperatures and voltage/currents for safe operation
 - use addressable sensors to permit large numbers of sensors
- Safemode entry on anomalies or command silence
- Dual watchdog timers for load-shedding and resets
- Programmed in C (hardware control) and Basic(operations)

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Design: Flight software

- Control law and body motion modeling developed by Tom Flatley
 - sims showed:
 - GG capture by hysteresis rods
 - 1/4 arcsec stability over 15 second control law cycle
- Tom's code converted to a body simulation and to flight code by P.I.
- All code for telemetry, attitude control law, battery management, orbit models, magnetic field models, downlink scheduling, thermal monitoring, and RF control written by P.I.
- All code for hardware control (3200 Hz interrupt routine), payload camera operation, image analysis, pattern recognition, and ground telemetry processing written by volunteer (DJS).
- All design and testing was set up and executed by P.I. and DJS

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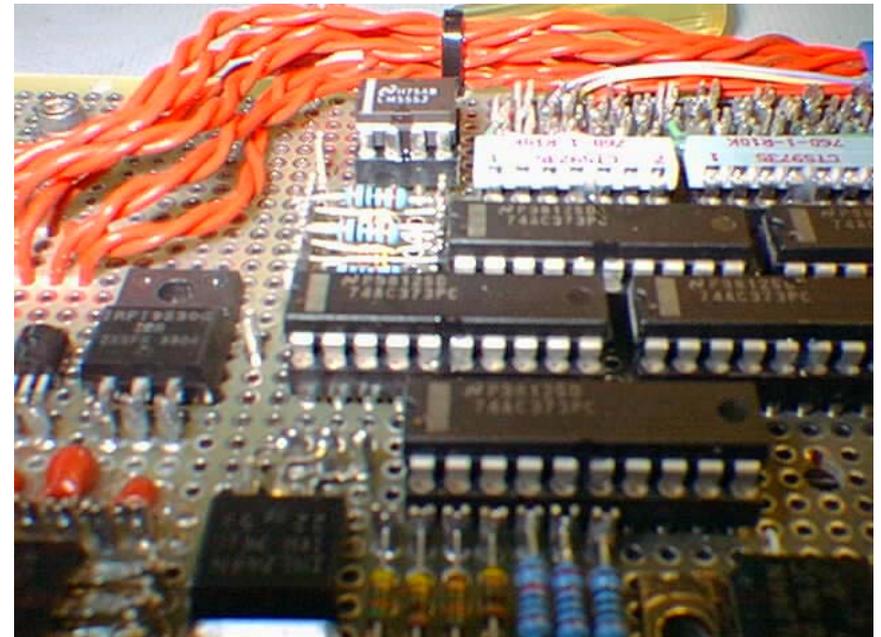
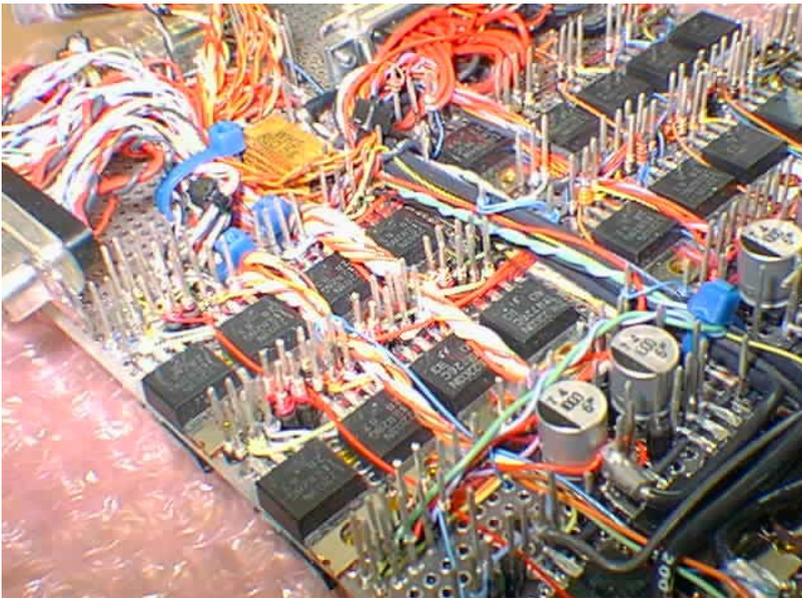
Design: Nominal Operation

- **Awaken via watchdog timer and wait for batteries to reach 80% charge**
- **Stay in safemode with Rx on continuously until ground contact**
 - ground will uplink NORAD TLE and UT time
 - can then calculate local magnetic field vector
 - calculate AOS/LOS times and perform autonomous downlink
- **Turn on GPS to acquire inertial attitude (ECEF quaternions)**
- **Use attitude/mag field info to dump excess reaction wheel momentum**
- **Slew to target with 1 degree accuracy using GPS**
- **Put camera into control loop using stars of opportunity**
 - use 2x2 deg uplinked star catalog to pattern-match field
- **Open-loop offset to target/guide stars, commence target observations**
- **Turn off GPS until target sets**

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Flight Electronics Design and Construction

- Power distribution board (left), I/O expansion board (right)
- Two circuit boards needed to glue commercial components together
- All electronics designed, built, and tested by P.I.



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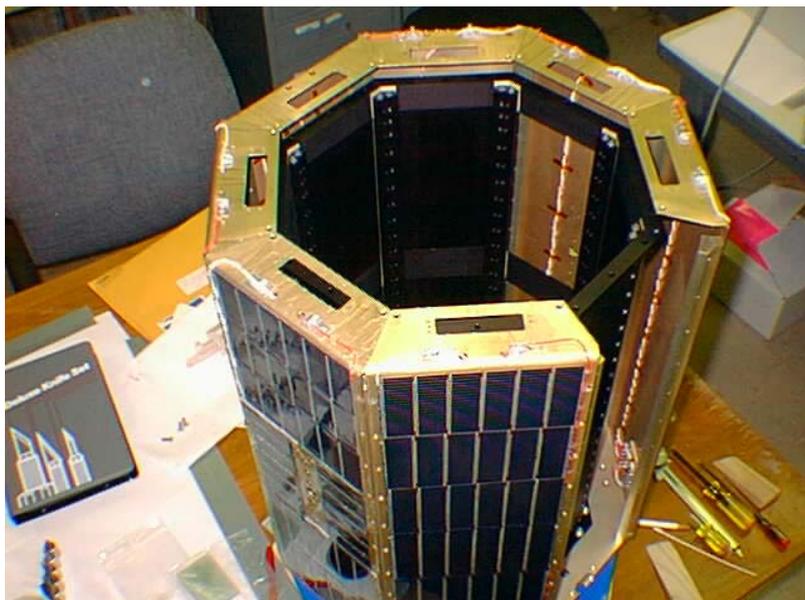
Mechanical Design and Construction



- Detailed design by 4th year U. Md. undergrad in Mechanical Engineering
 - all aluminum - no composites or exotic materials
 - full Pro Engineer CAD/CAM model created
 - Autocad drawings of parts provided to local commercial fab houses
 - full certs obtained for all materials, processes, and coatings
- Baseplate validation with HitchHiker hardware early in cycle

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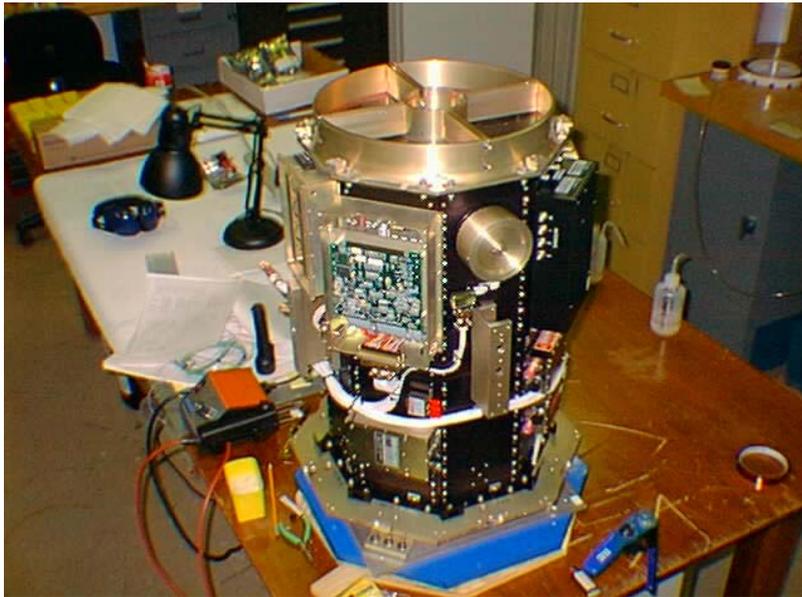
Mechanical Construction



- Octagonal body plan to fill HitchHiker canister efficiently
- Solar arrays body-mounted on sheet metal panels
- All electronics boxes mounted between telescope enclosure and solar array panels (8x2.5"x7"x22")
- Science camera mounted on a focus table (0.2" throw)
- Reaction wheels mounted on body axes to simplify computer code

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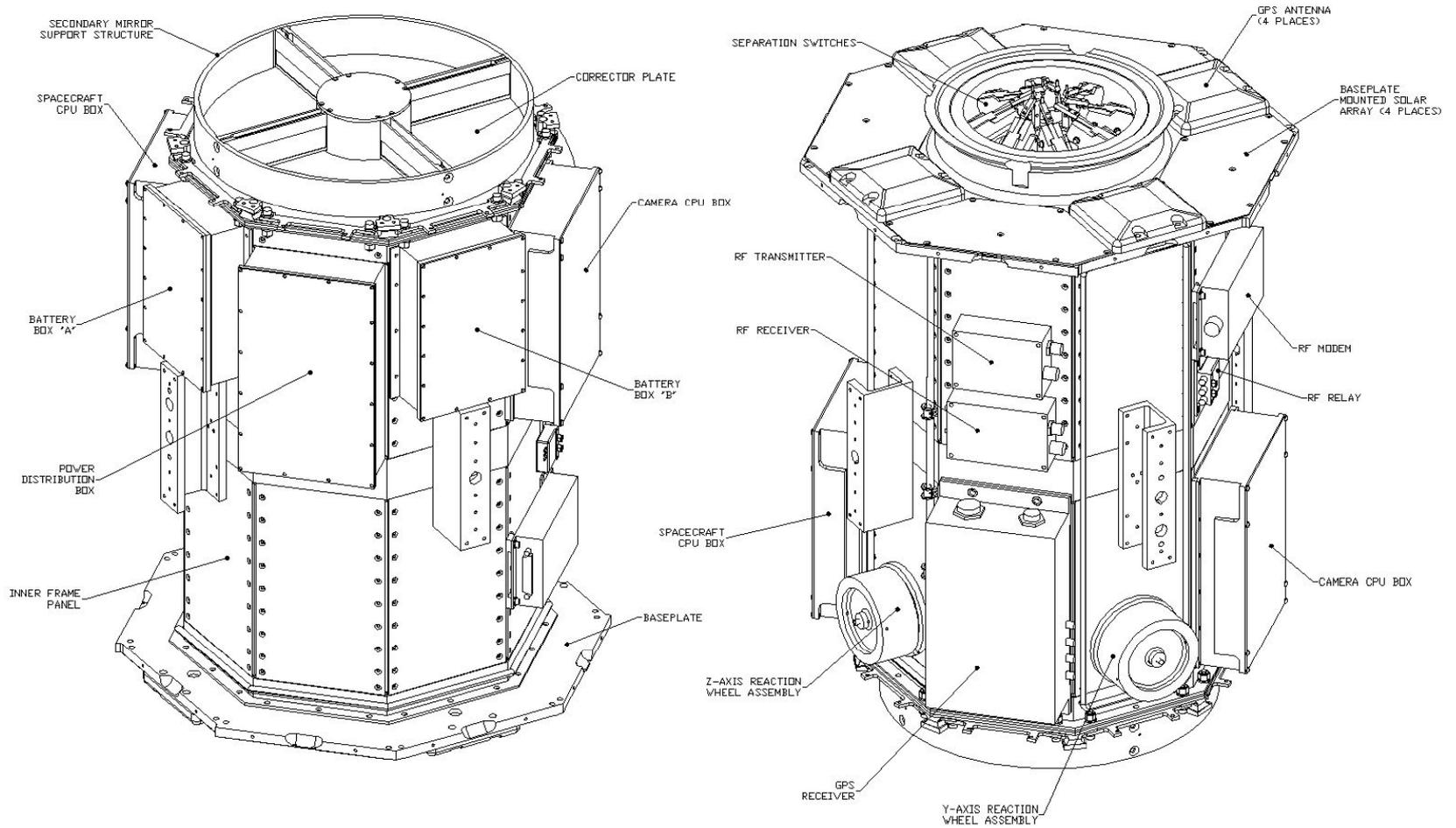
Mechanical Assembly



- Spacecraft early assembly
 - computer
 - reaction wheel
 - battery box
 - GPS receiver
 - RF equipment
 - cabling
 - secondary mirror assembly
 - entrance window
 - baseplate (19" dia)
 - overall height 26"

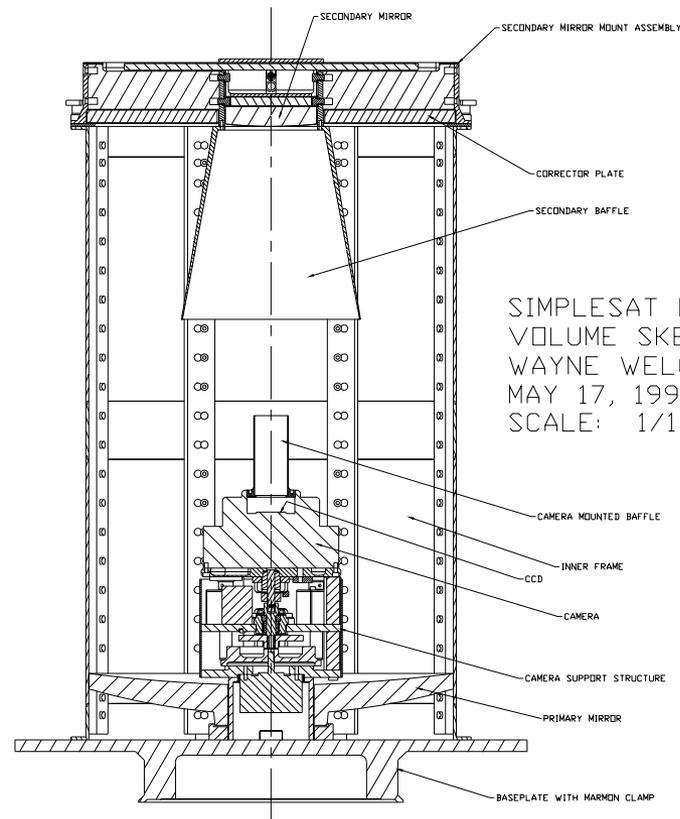
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Mechanical Assembly



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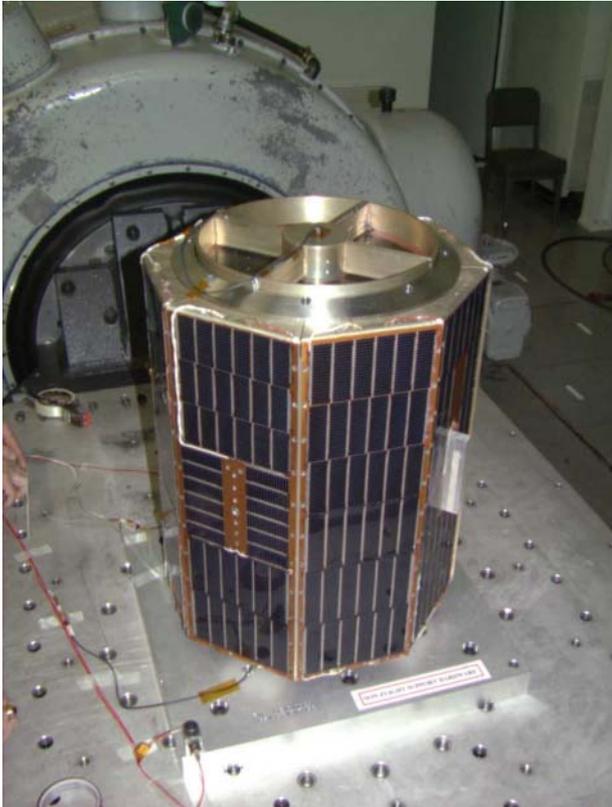
Spacecraft Cross-section



SIMPLESAT OPTICS
VOLUME SKETCH.
WAYNE WELCH
MAY 17, 1998
SCALE: 1/1

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Safety Testing



- Spacecraft safety testing
 - 12g rms 2-axis vib
 - to GEVS levels
 - primary mirror bond separation
 - 8g rms 3-axis vib retest
 - to predicted levels
 - successful
- Mech interference with separation mechanism resolved
- Conformal coating on solar array baked out to meet spec

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Ground Testing Performed

- CPU boxes vacuum tested at roughing pump pressures
- Electrical wakeup
- Center of Mass Determination
- (Indoor) RF Link Validation (coax and attenuators)
- Uplink/Downlink data end-to-end validation
- Solar array bakeout
- GPS self-survey
- Stand-alone operation (powered by array in sunlight) on roof of B33
- Multi-day orbit sims in lab
- Specialized thermal tests on battery cells and glass bonds

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*Testing **NOT** done*

- Box and S/C Thermal Vacuum (other than CPUs)
- Ambient Pressure Temperature Cycling
- Mass Properties (other than CG)
- Anechoic RF Chamber
- Outdoor RF Link Validation
 - ground station constructed and tested after s/c delivery
- S/C Level Bakeout
- Sine Burst Strength Test

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Studies/Documents required by GSFC for SimpleSAT-1

- Safety Verification Plan
- Vibration Test Plan
- Fracture Control Plan
- Stress Analysis
- Phase 0/1 and Phase 2/3 Reports
- Hazard Reports
- Venting Analysis (spacecraft and boxes)
- Cargo Bay Floodlight Effects
- RF Safety Analysis
- Battery Safety Analysis
- Ejection Trajectory Analysis
- Mirror Repair Summary

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Launch Preparations



- Spacecraft safety validation
 - Battery depletion
 - Optical cleanliness
- Ground station completion

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STS-105 Launch/Deployment



- 10 August 2001



20 August 2001

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Initial Spacecraft Operating Mode

- Simplesat-1 passive until batteries reached state-of-charge=0.8
- Assumes CPU came to life correctly
- Rx should have come on at SOC=0.8 along with coil to force tumble
- Beacon not allowed due to RF license restrictions
- Mode should have been: tumbling, waiting for RF uplink
- No wheels, GPS, or payload activity permitted
- Should have been able to hold this mode indefinitely
 - Power margin was not great (5% per orbit) with RF on constantly

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Initial Operations Attempts

- Jeff Houser, Ron Parise, and Marco Midon of the GSFC ham radio club worked closely with me to improve the Simplesat-1 ground station
- Process took several weeks
 - Downlink sensitivity verified with LO-19 detection
 - Uplink RF levels verified by Jeff, et.al. at radio club
- Spacecraft was unattended all this time
- Wallops attempted to detect RF activity but heard nothing
- No remaining inexpensive improvements available
- With new ground station in place, still no contact
- With many changes in RF configuration it is not clear when the first valid uplink command might have been received (triggering Tx)
- **Conclusion:** trouble most likely on spacecraft

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Possible Spacecraft Failure Modes

- Simplesat-1 was a single-string design
 - Any wire or part failure would have caused mission failure
- Any of the eight separation switches failing would have prevented the spacecraft electronics and battery charging from operating correctly
- Batteries may not have charged correctly prior to CPU wakeup
- Watchdogs may not have awakened CPU
- Batteries may not have reached an acceptable state-of-charge to enable RF system
- Solar arrays may not have provided adequate power to charge batteries or meet the spacecraft safemode power requirements
- State-of-charge circuit may not have functioned correctly
- RF Rx may not have sensed acceptable FM signal with correct modulation
- “Beep” command may not have turned on Tx and enabled brief downlink
- Tx may have failed due to unexpected corona sensitivity

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Wire/part failures

- Spacecraft went through two major vibration tests
- No electronics failures from either shake
- No connector problems experienced prior to launch
- No wire-related failures prior to launch
- No part failures prior to launch

- No reason to expect a wire failure on orbit

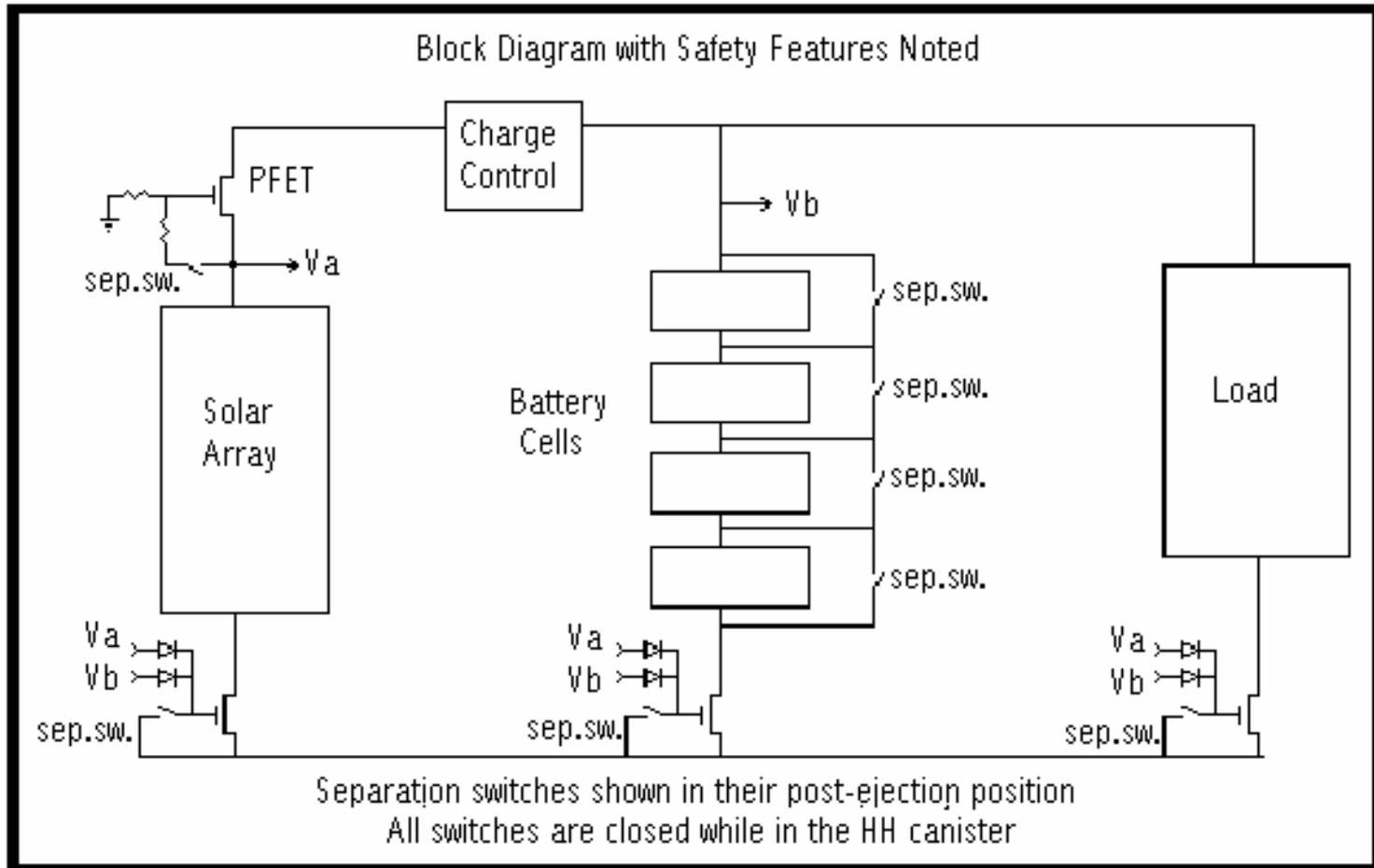
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Separation Switch Failure

- Four sep switches bleed battery down - one switch per cell
 - Four cells (1.25 volt NiCd 15 A-hr) in series
 - no cell reversal possible unless a switch fails
- Four sep switches control overall current distribution
 - Two breaks in solar array leg (at top and bottom of array)
 - One break on load leg
 - One break in battery leg
- All switches performed correctly in vib tests and on the bench
- Surrey pointed out possible switch failure mode
- Inspection of ejection videos shows no external damage to spacecraft

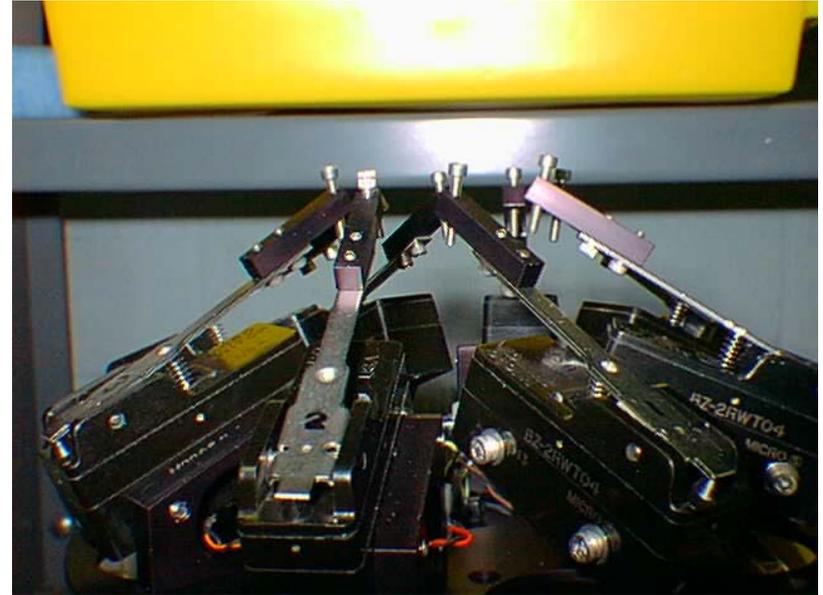
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Spacecraft Power System



Separation switch mounting plate

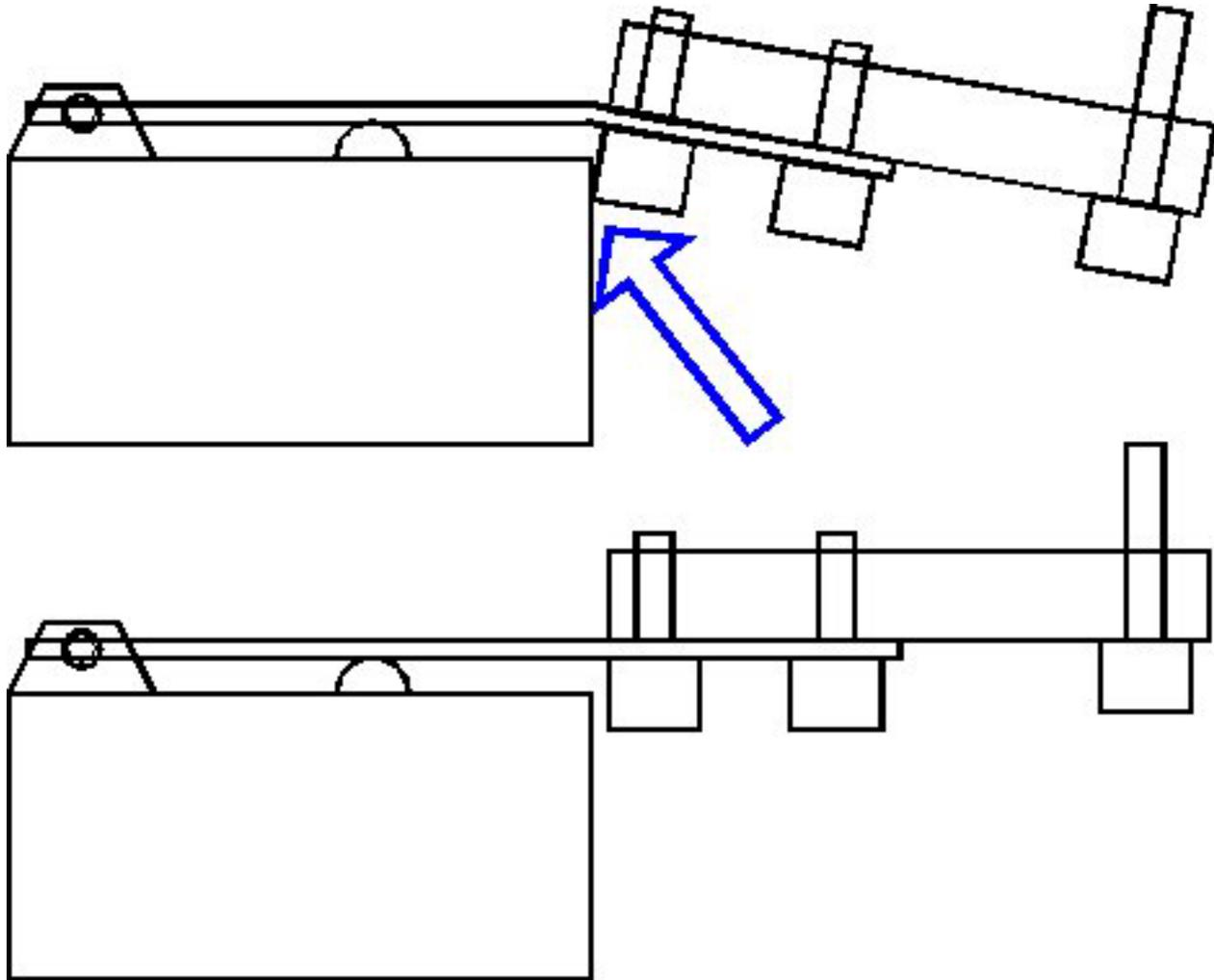
- each arm adjustable to mate with push plate



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Possible Separation Switch Failure Mode (from Surrey)

- our investigation shows adequate clearance
- would have shown up in the two vib tests



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Battery Initial Charge Failure

- Batteries in fully discharged state at room temperature for 6 months
- IUE experience indicates that this is acceptable for NiCd's
- Many tens of Simplesat lab tests were run, using power supplies to substitute for the solar array, all with wake-up success

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IUE experience with NiCd storage

Further work to evaluate the effects of long-term storage was initiated in 1985. Cells purchased for the IUE program and stored at the GSFC for a period of 9 to 11 years at room temperature (discharged and shorted) were subjected to a repeat of the original acceptance test (Ref. 46) and then placed on life test. The test regimes included a LEO and synchronous orbit and a standard set of test conditions used on cells from this lot when they were new. After 4 years, testing of these packs was discontinued because of lack of funding. At the time the test was terminated, the pack on LEO cycling had completed 21,000 cycles, and the pack on GEO cycling had completed 42 shadow periods (Ref. 2).

There was no measurable difference in the lifetime between these cells, and those from the same cell lot tested several years earlier. This test provided one additional data point indicating that the cycle life of NiCd cells is not appreciably affected by wet storage life after 9 years, even at room temperature with the cells shorted. The results of this test on

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Watchdog/CPU Circuitry Failure

- Watchdogs functioned reliably down to 1.5 volts in bench tests
- 555 timer sends pulse to CPU card once per minute
 - need adequate time for reset to take effect and software to load/execute
- Watchdog signal sent to opto-isolated reset on CPU board
- Worked reliably in all lab tests prior to launch
 - Flight CPU was always reset correctly
- Newer CPUs did not reset correctly
 - Recent versions of 6040 CPU needed full power cycling to recover
 - Similar behavior on orbit would have caused mission failure

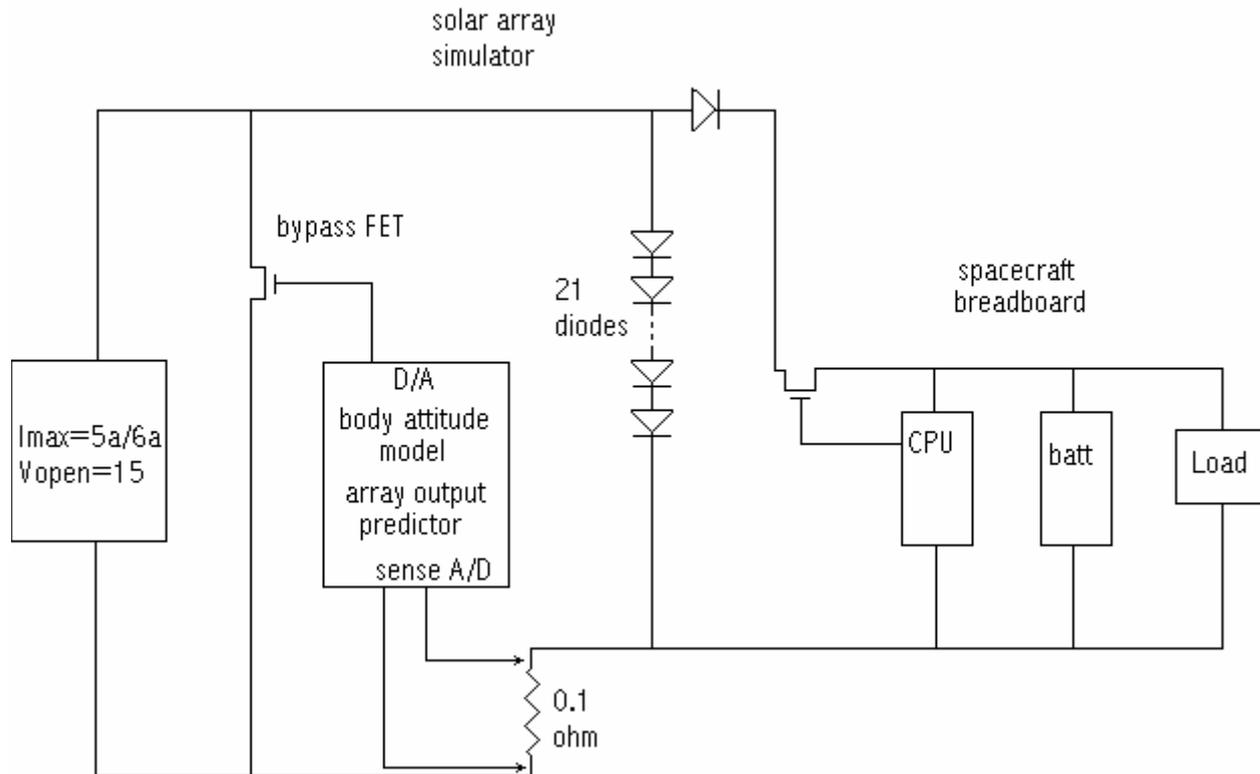
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Solar Array Under-Performance

- An under-performing array could cause mission failure by not being able to maintain safemode power while tumbling
- Baseline solar array panel performance was measured in atmosphere
- Spacecraft was able to charge batteries in an outside stand-alone test on solar array power only with the Sun at 30 deg elevation
 - equivalent to 50% illumination (2 airmasses at 70% trans/airmass)
- Electrical simulator constructed to feed power to breadboard
 - duplicated the I-V curve of the actual array
 - illumination levels calculated from high fidelity attitude model
- Multi-day orbit simulations run to determine system startup and early operations characteristics

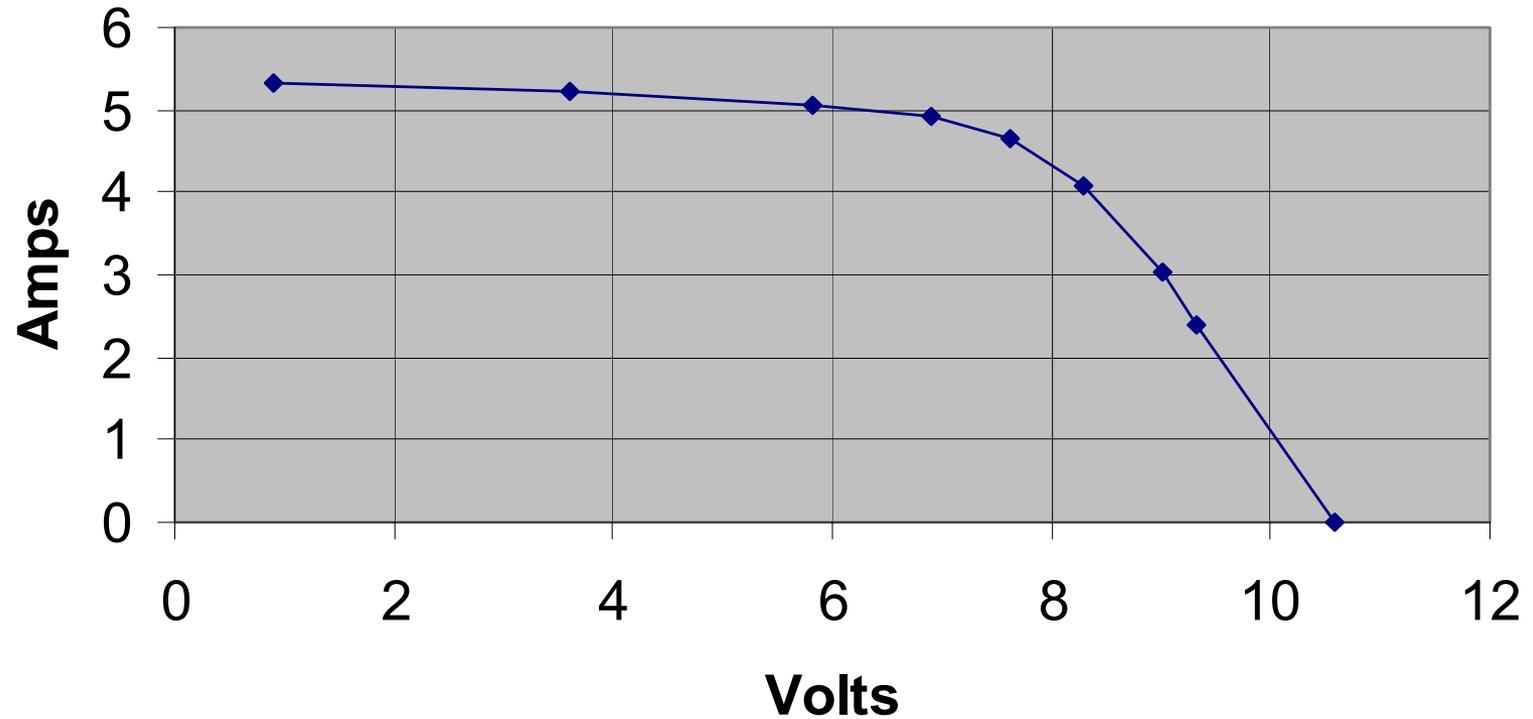
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Solar-Array and S/C Breadboard



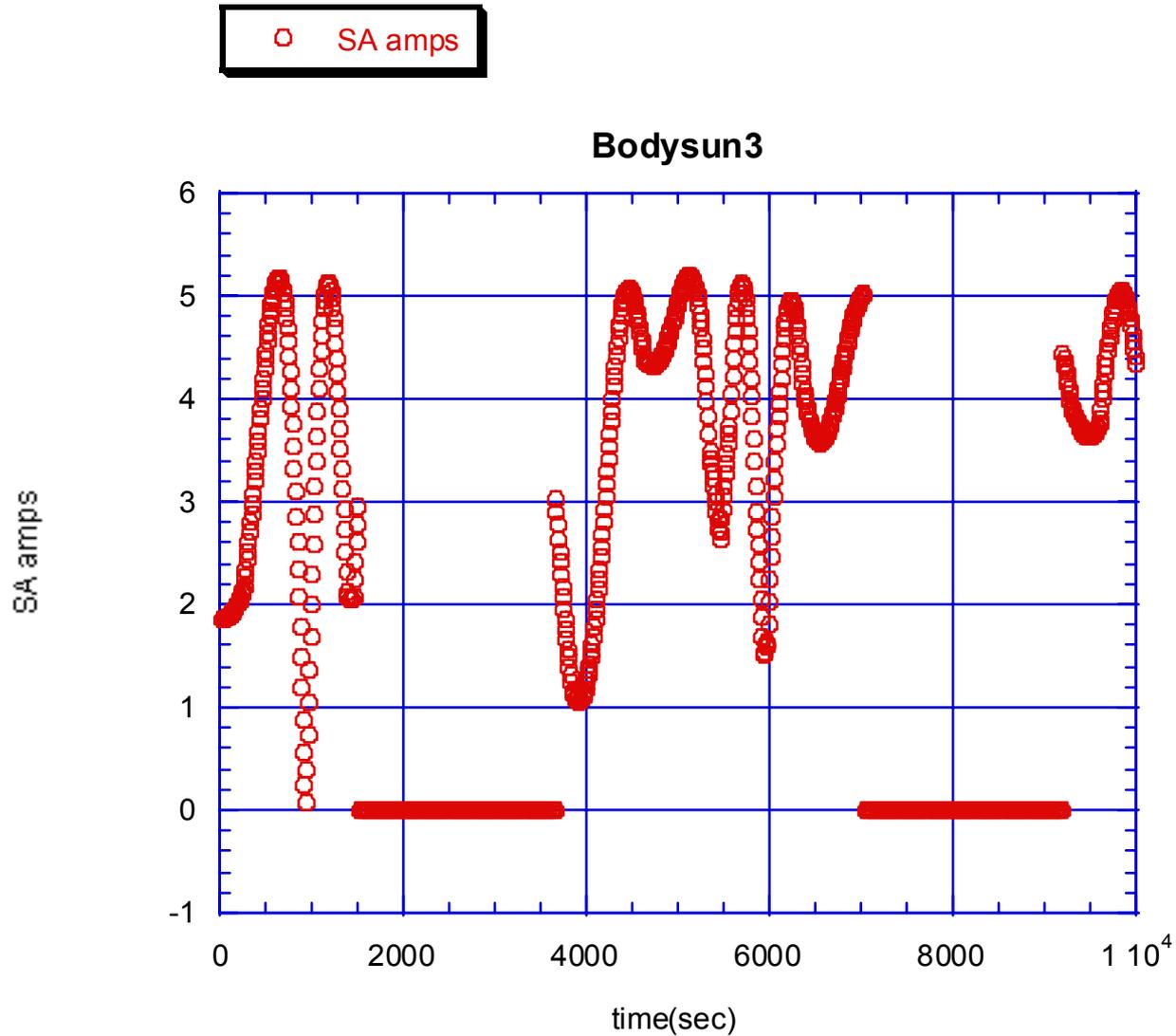
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Solar Array Simulator I-V Curve



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Typical Solar Array Output Variation (Tumbling)



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S/C Breadboard Performance with Simulated Solar Array

- Breadboard performed well, even when stressed
- All runs started with fully discharged cells
- No RF equipment available, resistors used to simulate loads
- All wake-ups were accomplished successfully with older CPUs
 - CPU undervoltages at each first eclipse, survives all following eclipses
- Solar array output should have been adequate even at minimum
- Flight software performed correctly
 - handled all command inputs correctly
- Battery charge FET gate voltage was not optimal
 - 5 volt max just barely adequate to limit battery overcharging
 - lesson: use 10v
- State-of-Charge circuit performed correctly
- New CPUs sometimes failed to boot cleanly
 - lesson: use power cycling rather than reset line

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RF Link Failure

- Failure of initial contacts due either to spacecraft problems or to problems with the new ground station
- Calculated link margins looked good
- Radios were opened and modified pre-launch to increase audio bandwidth but pulse-shape fidelity was still not optimum (modem 100 usec pulse width)
- Ground station equipment had performed acceptably in lab with cables, hats, and attenuators but at elevated levels (-50 to -60 dbm)
 - unable to quiet lab environment
 - unable to define/execute acceptable low-cost outdoor test
- Ground system reworked several times in first month
 - Transverter downlink section found to have low sensitivity
 - Separate radio added for direct downlink, frequency generators added
 - Expected uplink to be ok, most problems were with the downlink
 - RF Tx power measured and found adequate
 - Additional RF power amplifier added (20W boosted to 100W)

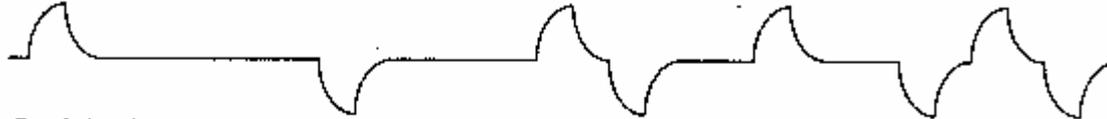
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RF Comm System Data Waveforms

DATA
INPUT
TO
MODEM

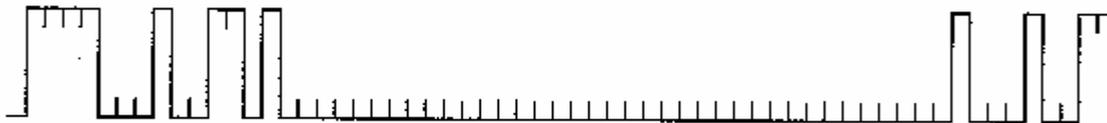


DATA
OUTPUT
FROM
MODEM



Note: For clarity of presentation,
propagation delay through
the modem is not shown.

a) Typical Random Waveform



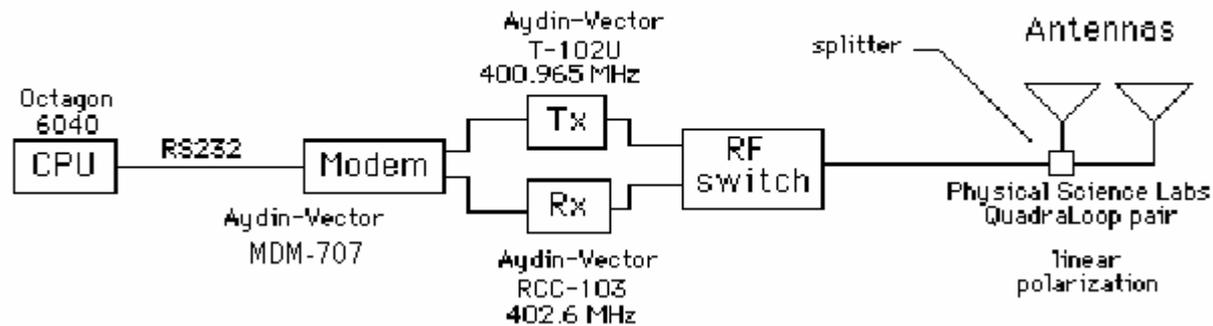
b) Effect of No Transitions in Data

Figure 2, Transmit Waveforms

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Spacecraft RF System

Spacecraft RF system block diagram



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Searching for Downlink

- NORAD two-line-elements (TLE) emailed to PI every day
- Gimbal-mounted Yagi pointed to spacecraft using TLE
 - at AOS uplinked multiple ‘beep’ commands requesting downlink activation
 - listened for 20 seconds, then tried again, until predicted LOS
 - data polarity inverted on every uplink set
- Downlink receiver audio output digitized and saved to disk
- Used spectrogram analysis to search for 4800 baud signals
- Local signals seen, none from Simplesat-1
- Amateur sat LO-19 easily seen even with Yagi 10% off-frequency and with no preamplifier on mast
- Every Simplesat pass above 15 deg elevation was attempted

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Spectrogram Scanning for Simplesat-1 Signal

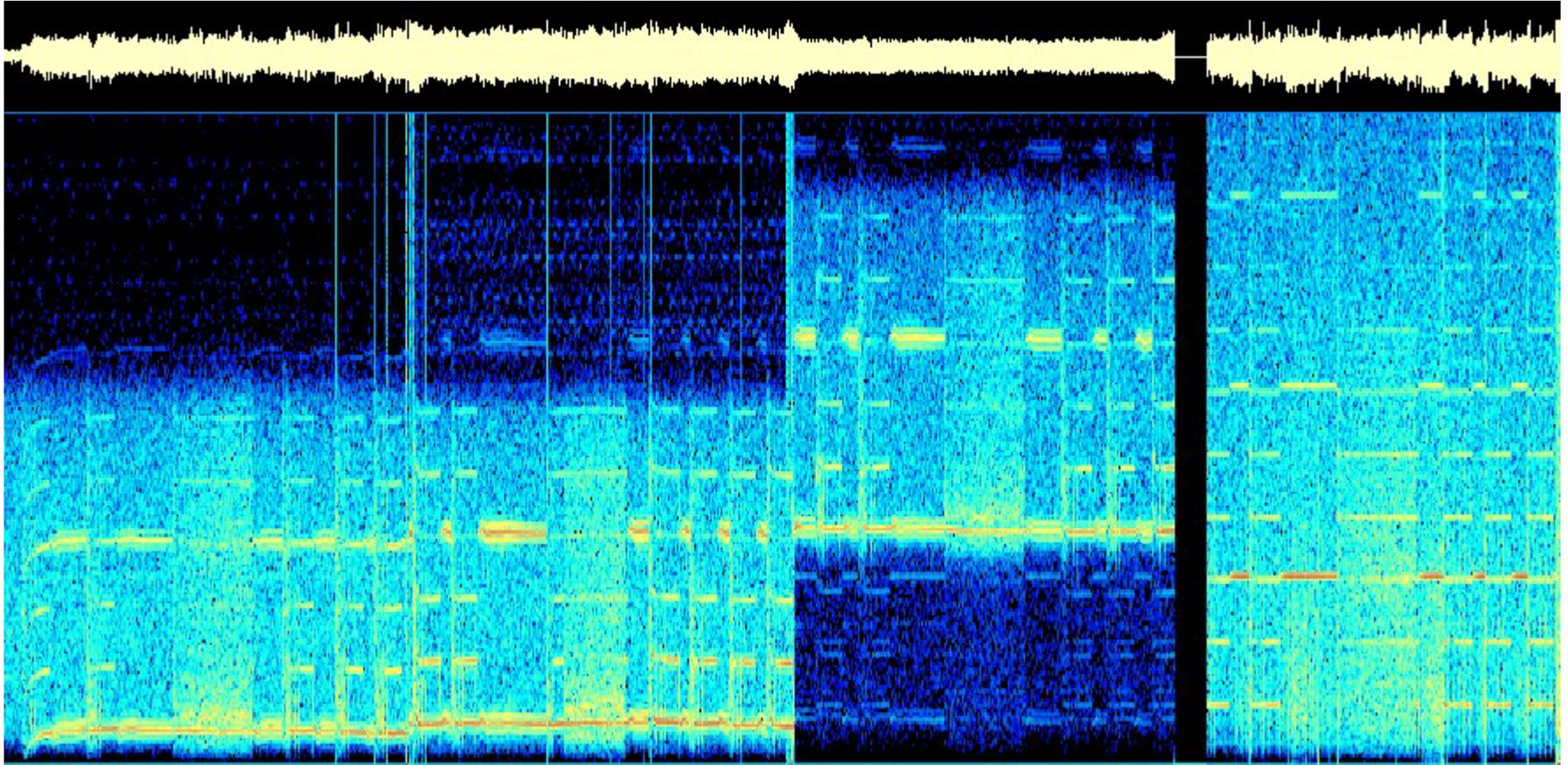
End-to-end Breadboard Beep Command Response Below

USB

CW

RTTY

FM



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Transmitter Corona Vulnerability Discovered

- From: vance.davis@te.L-3com.com
To: drskillm@pop900.gsfc.nasa.gov
Subject: RE: SimpleSAT Tx question
Date: Tue, 13 Nov 2001 17:11:53 -0500
- >I'd like to ask about the possible weakness of the T-102-U transmitter that I used on SimpleSAT. I did not order this Tx with any special high-altitude capability. Could you detail what weaknesses this Tx might have had in orbit?
- Since we did not perform Vacuum testing, we do not know if the unit is susceptible to corona. If corona occurred, it could have resulted in either high current draw by the transmitter, and no or low output power.
- >Would you estimate that it was likely to fail in this vacuum environment?
- It's pretty much a crap shoot.
- >Is there any prior experience that might cast light on this? Maybe some old vacuum test that your people did (for some other program) in which a similar Tx had either a problem or no problem?
- Some units will corona. Other units of the same design and construction will not. The fact that this is a relatively low power unit (2 watts), is in favor of NOT. Higher power units (5&10 watts) are much more susceptible to this problem. Corona typically occurs at altitudes of 20K to 50K feet. If the transmitter is in a pressurized compartment, corona is not likely. If the unit is exposed to 0 pressure, corona may occur.

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Transmitter Corona Mechanism

- Spacecraft transmitter power input +28 volts
- Voltage on antennas ~ 10 volts
- Final power stages of RF amplifier are impedance matched
- Early stages of RF amplifier are not impedance matched so resonant circuits can develop voltages in the 10v to 200v range
- These circuits are then susceptible to corona at low pressures
- Transmitter box was sealed with RTV gasket and hermetic connectors with unknown leakage
- Had been adequate for sounding rocket missions
- As the transmitter lost pressure on orbit it entered the corona pressure region at an unknown time and stayed there for an unknown duration
- It is not known when the first adequate uplink command was received by the spacecraft

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Conclusions

- \$200K + 5 MY was adequate to design and construct a small satellite, science instrument, and ground station
- Shuttle/HitchHiker launches coupled to the ISS orbit and its advantageous communications geometry makes satellite projects feasible for Universities
- A small science satellite can be designed and constructed by a small team
 - Small non-science satellites have been orbited by the ham radio community for years
 - Simplesat -1 attempted to add both coarse and precise pointing via GPS and star tracking
 - Can be used for Earth or space viewing experiments with lifetimes of a month plus
 - Could be constructed by smart novices who have absorbed the Simplesat experience
- Careful design can produce a satellite that meets Shuttle safety standards without requiring expensive studies or tests
- These satellites can be funded from sources outside NASA
- Our first attempt was Simplesat-1. We had no communications contacts in orbit. The most likely cause seems to be spacecraft transmitter arcing
 - it is not clear that this problem would have been caught by reviews or testing
- More workmanship and RF testing seems needed compared to Simplesat-1
- Assistance from NASA will be needed for specialty items (GPS receiver modifications, fasteners, etc.)

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What worked well

- Adapting solar race-car solar panel construction techniques
- Commercial CPUs needed only small modifications
- Commercial grade telescope optics performed well and were safe
- Corrector plate provided thermal isolation of optical volume
- Commercial grade star camera needed small mods but worked well
- Stepper-motor based ACS was well-behaved
- Commercial NiCds withstood abuse and had stable characteristics
- Adoption of discharged-battery approach simplified safety efforts
- Magnetic hysteresis rods and full body solar cell coverage for safemode
- Long optical focal length avoided aperture door requirement
- Bench access to sky via roof hatch
- Aircraft GPS unit was well behaved

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Lessons Learned

- Relax center-of-pressure requirement to create mass margin
- Run more box-level workmanship tests (thermal cycling in modest vacuum)
- Devise better RF tests to validate end-to-end data link before delivery
- Use S-band instead of UHF to avoid licensing problems
- Include an RF beacon capability
- Make solar panels flat (lip caused problems)
- Find higher efficiency solar cells to create more on-orbit power
- Use a lower outgassing conformal coating on the solar cells
- Convert wire-wrap cards to printed circuit cards
- Eliminate focus mechanism with isothermal optics spacing
- Move state-of-charge function into software
- Allow more voltage swing on FET gates
- Explore sub-stepping of reaction wheel motors to permit better slew performance